

VARIATION OF SOLAR IRRADIANCE AND MODE FREQUENCIES DURING MAUNDER MINIMUM

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Abstract. Using the sunspot numbers reported during the Maunder minimum and the empirical relations between the mode frequencies and solar activity indices, the variations in the total solar irradiance and 10.7 cm radio flux for the period 1645 to 1715 is estimated. We find that the total solar irradiance and radio flux during the Maunder minimum decreased by 0.19% and 52% respectively, as compared to the values for solar cycle 22.

1. Introduction

The period of low solar activity between 1645 to 1715 is commonly known as the Maunder minimum and has attracted attention of researchers as it put forward many unexpected questions. During this period, the sunspots were infrequent and as a result it was assumed that the solar dynamo and the solar wind were either weak or switched off. Anomalies in the surface differential rotation during the Maunder minimum (Ribes and Nesme-Ribes, 1993) also point out the global changes in the internal solar dynamo mechanism. Measurements of ^{10}Be concentration in the Dye 3 ice core (Beer, Tobias, and Weiss, 1998) recently showed that the magnetic cycles persisted throughout the Maunder minimum, although the Sun's over all activity was drastically reduced. This period is also associated with the so called "little ice age" in Europe and Eddy (1976) suggested that it might be due to a decrease in solar irradiance. Many authors have estimated the total solar irradiance during the Maunder minimum and find a decrease in the range of 0.1% at a time of relatively high activity down to 1% at a time of no or low activity.

In a different approach, we estimate the change in the total solar irradiance and 10.7 cm radio flux during the Maunder minimum. This is achieved by calculating the p -mode frequencies using the historic record of sunspots and the empirical relations derived by Jain *et al.* (2000). Since these relations between mode frequencies and solar activity indices are shown to be independent of solar cycles, these can be reliably used to estimate variations in solar irradiance and radio flux.



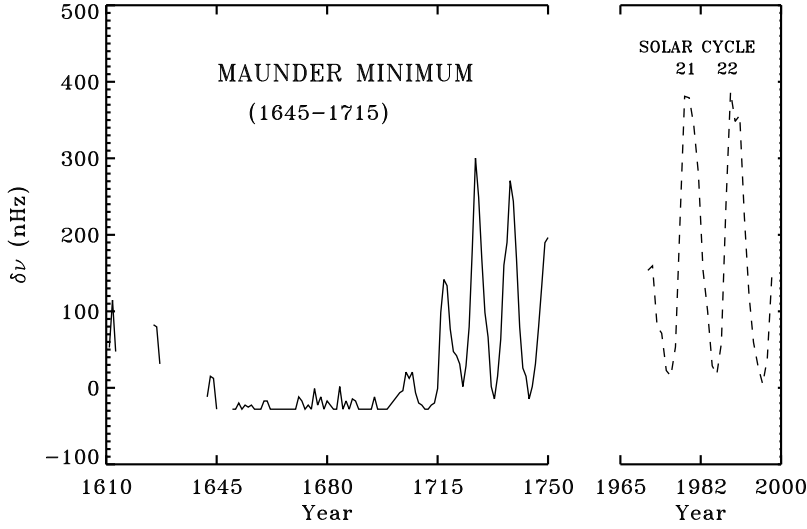


Figure 1. Estimated frequency shift for the period 1610–1750 (solid line) and 1965–1998 (dashed line) with reference to the annual mean of 1996, using the mean annual sunspot number from Eddy (1976) and Equation (1).

2. Estimates during Maunder Minimum

2.1. p -MODE FREQUENCIES

We estimate the change in p -mode frequencies during the Maunder minimum using the following relation derived by Jain *et al.* (2000):

$$\delta\nu = (2.41 \pm 0.19) \delta R_s - (0.48 \pm 1.68), \quad (1)$$

where $\delta\nu$ is given in nHz and R_s is the smoothed sunspot number. The estimated $\delta\nu$ for the epoch 1610 – 1750 and 1965 – 1998 using the mean annual sunspot numbers from Eddy (1976) and Equation (1) is plotted in Figure 1. It is observed that during the deep Maunder minimum (1655–1685), the frequency shifts are negligible corresponding to the low or no solar activity period. The maximum change in the p -mode frequencies during the entire period is found to be 43 ± 3 nHz, which corresponds to 11% of the maximum change during the solar cycle 22. This small change in frequency may be interpreted as due to the internal structural stability in the Sun during that period.

From the historic photoheliographic records, Ribes, Ribes, and Bartholot (1988) and Ribes and Nesme-Ribes (1993) have shown that the solar diameter during the Maunder minimum increased by 7 arc

seconds, as compared to the present value. Delache *et al.* (1993) have studied the correspondence of p -mode frequency shifts with solar radius and neutrino flux and found that $\delta\nu$ is anticorrelated with both. From these findings, we infer that during the Maunder minimum, the neutrino flux would have increased from the present day value. This indicates that there was a real expansion of the solar envelope during this period and a decrease in solar surface temperature and irradiance. These observed correlations between the solar activity, p -mode frequencies, solar radius, neutrino flux and solar irradiance, strongly suggest the possibility that the dynamical processes occurring in the upper layers are closely related to the perturbations inside the Sun, perhaps even down to the core.

2.2. TOTAL SOLAR IRRADIANCE AND RADIO FLUX

Since the Sun's radiation is the principal driving force for global climate, the variation in total solar irradiance (TSI) may lead to the climatic change. The coincidence of Maunder's "prolonged solar minimum" with the coldest period in Europe has been reported earlier. It was suggested by Eddy (1976) that this cold period might be due to the reduction in solar irradiance. The estimates for solar irradiance during the Maunder minimum have been provided by many workers and they have found a decrease with respect to the present value. To obtain an independent estimate of the variation of the solar irradiance, we follow Jain *et al.* (2000) and derive the following relation between $\delta\nu$ and δTSI :

$$\delta\nu = (68 \pm 16.4) \delta TSI - (9.12 \pm 2.09) \quad (2)$$

Using this relation and the value of $\delta\nu$ for the Maunder minimum obtained earlier, we estimate that the total solar irradiance during Maunder minimum decreased by 2.68 W/m^2 (0.19%) from the average value of 1366.06 W/m^2 for cycle 22. Reid (1991) had found that the TSI during Maunder minimum was lower by 1% than the value for 1980. Using empirical correlation between TSI and the integrated Ca II emission, Lean, Skumanich, and White (1992) suggested a decrease between 0.15% and 0.35%. Nesme-Ribes and Mangeney (1992) obtained a 0.2% decrease in the irradiance by comparing the variation in the differential helio-latitudinal rotation during the Maunder minimum and present time. Nesme-Ribes *et al.* (1993) calculated an average decrease of 0.25%–0.5% in luminosity using the solar radius measurements. They had assumed an anticorrelation between the Sun's diameter and its luminosity. Mendoza (1996) modified these values to 0.11%–0.43% using the Maunder minimum sunspot numbers and near-equatorial rotation

rates. Further, from the contemporary and past rotation rates and solar radii, Mendoza (1997) reported a decrease of 1.23% in TSI for the year 1683, when there were almost no sunspots and 0.37% for the year 1715, when solar activity begun to rise. Thus, our estimate of TSI fairly agrees with the earlier results using different activity indicators or physical parameters.

From the estimated change in frequency during the Maunder minimum and the following equation from Jain *et al.* (2000)

$$\delta\nu = (2.66 \pm 0.20) \delta F_{10} - (4.67 \pm 1.44), \quad (3)$$

we calculate the change in 10.7 cm radio flux during Maunder minimum. As compared to 128 sfu - the average value for cycle 22, the radio flux is found to decrease by 66.2 sfu *i.e.* by 52% during the Maunder minimum.

3. Conclusion

Using the historical sunspot data and the empirical relations between the p -mode frequencies and activity indices derived by Jain *et al.* (2000), it is estimated that during the Maunder minimum from 1645 to 1715 AD, the mode frequencies showed a maximum change of 43 ± 3 nHz. Using the derived mode frequencies as a proxy of the solar activity indicators, we have further estimated the total solar irradiance and 10.7 cm radio flux and find that these are lowered by 0.19% and 52% respectively than the average values of the solar cycle 22. The decrease in p -mode frequency and irradiance during Maunder minimum probably indicates stability in the dynamical processes occurring in the solar convection zone and even deep down up to the core.

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